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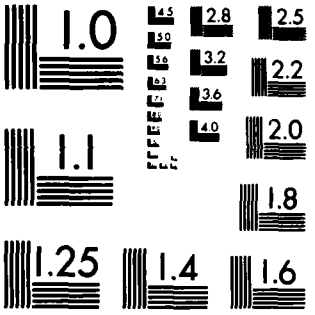

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The main objective of our research is the study of new algorithms and implementations suitable for VLSI. A primary assumption in this research is that algorithms must match the available computational resources in order to obtain efficient algorithms. The starting point is not the algorithm for a specific class of digital processing problems; the starting point is the resource available for computing. The characteristics of this resource dictate what will be effective and efficient. VLSI technology presents digital signal processing with a unique environment with special qualities not heretofore used in computation. Each class of processing problems coupled with VLSI technology requires new algorithms for effective use of VLSI chips. Thus, our research has considered several classes of problems and various algorithms for each class. We have also considered certain theoretical problems associated with the representation of processing systems. The reason alternate representations are important is that they suggest new and more general methods of uniting different processing tasks.

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1. C. T. Mullis and R. A. Roberts, "Digital Processing Structures for VLSI Implementation," *Proceedings of International Conference on Acoustics, Speech, and Signal Processing*, San Diego, April 1984.

2. R. A. Roberts and B. D. Van Veen, "A Digital Filter Structure for Efficient VLSI Implementation," *Proceedings of the Eighteenth Annual Asilomar Conference on Circuits, Systems, and Computers*, Pacific Grove, CA, November 1984.

3. R. D. DeGroat and R. A. Roberts, "Accurate Frequency Estimation of a Single Sinusoid in Noise," *Proceedings of the Eighteenth Annual Asilomar Conference on Circuits, Systems, and Computers*, Pacific Grove, CA, November 1984.

4. C. T. Mullis and R. A. Roberts, "Digital Processing Structures for VLSI Implementation," *VLSI Signal Processing*, IEEE Press, New York, NY, 1984.

5. R. A. Roberts and C. T. Mullis, "Digital Processing Structures for VLSI Implementation," *Proceedings of the International Conference on Acoustics, Speech, and Signal Processing*, Tampa, Florida, April 1985.

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8. R. A. Roberts and C. T. Mullis, "Orthogonal Filters for VLSI Implementation," *Proceedings of Nineteenth Annual Asilomar Conference on Circuits, Systems, and Computers*, Pacific Grove, CA, November 1985.

9. C. T. Mullis and Louis L. Scharf, "Internal Projections for Rank Reduction in Linear Dynamical Systems," *Proceedings of Nineteenth Annual Asilomar Conference on Circuits, Systems, and Computers*, Pacific Grove, CA, November 1985.

10. R. A. Roberts and B. D. Van Veen, "A General Framework for Analysis of FIR Beamforming Structures," *Proceedings of Nineteenth Annual Asilomar Conference on Circuits, Systems, and Computers*, Pacific Grove, CA, November 1985.

11. B. D. Van Veen and R. A. Roberts, "A Design Technique for Partially Adaptive Arrays," *Proceedings of Twentieth Annual Asilomar Conference on Circuits, Systems, and Computers*, Pacific Grove, CA, November 1986.

12. R. D. DeGroat and R. A. Roberts, "Highly Parallel Eigenvector Update Methods with Applications to Non-stationary Signals," *Proceedings of Twentieth Annual Asilomar Conference on Circuits, Systems, and Computers*, Pacific Grove, CA, November 1986.

13. R. D. DeGroat and R. A. Roberts, "Update Eigenvector Methods for Non-stationary Signals," *Proceedings of SPIE Conference on Advanced Algorithms for Signal Processing*, San Diego, CA, August 1986.

14. C. T. Mullis and C. J. DeMeure, "The Jury Matrix and a Newton-Raphson Procedure for MA Spectral Factorization" *Proceedings of Twentieth Annual Asilomar Conference on Circuits, Systems, and Computers*, Pacific Grove, CA, November 1986.

15. C. T. Mullis, J. C. Franchitti, and German Feyh, "A Filter Interpolation and Frequency Transformation Problem," *Proceedings of Twentieth Annual Asilomar Conference on Circuits, Systems, and Computers*, Pacific Grove, CA, November 1986.

16. R. D. DeGroat and R. A. Roberts, "An Improved, Highly Parallel Rank-one Eigenvector Update Method with Signal Processing Applications," Proceedings of the International Conference on Acoustics, Speech, and Signal Processing, Dallas, TX, April 1987.

17. B. D. Van Veen and R. A. Roberts, "Analytic Design of Broad Band Partially Adaptive Beamformers," *Proceedings of the International Conference on Acoustics, Speech, and Signal Processing*, Dallas, TX, April 1987.

18. C. J. DeMeure and C. T. Mullis, "On the Fast Computation of Covariance and Cross-covariance Sequences," submitted to the *IEEE Transactions on Acoustics, Speech, and Signal Processing*, September 1987.

19. G. Feyh, W. B. Jones, and C. T. Mullis, "An Extension of the Shur Algorithms for Frequency Transformations," submitted to the *IEEE Transactions on Acoustics, Speech, and Signal Processing*, July 1987.

20. B. D. Van Veen, "Eigenstructure Based Partially Adaptive Array Design," submitted to the *IEEE Transactions on Acoustics, Speech, and Signal Processing*, June 1987.

21. C. T. Mullis, "Rational Approximations with Internal Projections," *Proceedings of Twenty-first Annual Asilomar Conference on Circuits, Systems, and Computers*, Pacific Grove, CA, November 1987.

22. B. D. Van Veen and R. A. Roberts, "Partially Adaptive Beamformer Design via Output Power Minimization," *IEEE Transactions on Acoustics, Speech, and Signal Processing*, ASSP-**35**:11, November 1987.

23. B. D. Van Veen, "A Comparison of Two Approaches for Partially Adaptive Beamformer Design," submitted to the *IEEE Transactions on Acoustics, Speech, and Signal Processing*, July 1987.

24. B. D. Van Veen and R. A. Roberts, "A Systolic Array for Partially Adaptive Beamforming," *Proceedings of Twenty-first Annual Asilomar Conference on Circuits, Computers, and Systems*, Pacific Grove, CA, November 1987.

25. R. D. DeGroat and R. A. Roberts, "Time-varying, Rank-one Signal Subspace Updating," *Proceedings of Twenty-first Annual Asilomar Conference on Circuits, Computers, and Systems*, Pacific Grove, CA, November 1987.

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28. R. D. DeGroat and R. A. Roberts, "A Family of Rank-one Updating Methods," *Proceedings of the Singular Value Decomposition and Signal Processing Workshop*, Les Houches, France, September 1987.

29. R. D. DeGroat and R. A. Roberts, "A Family of Rank-one Signal Subspace Updating Methods," submitted to the *IEEE Transactions on Acoustics, Speech, and Signal Processing*, July 1987.

30. R. D. DeGroat and R. A. Roberts, "Efficient, Numerically Stabilized Rank-one Eigenstructure Updating," submitted to the *IEEE Transactions on Acoustics, Speech, and Signal Processing*, July 1987.

Research Findings—Final Report

Our research findings are contained in detail in approximately thirty publications as listed under Section 7. We shall briefly summarize some of the more important contributions.

The main objective of our research is the study of new algorithms and implementations suitable for VLSI. A primary assumption in this research is that algorithms must match the available computational resources in order to obtain efficient algorithms. The starting point is *not* the algorithm for a specific class of digital processing problems; the starting point is the resource available for computing. The characteristics of this resource dictate what will be effective and efficient. VLSI technology presents digital signal processing with a unique environment with special qualities not heretofore used in computation. Each class of processing problems coupled with VLSI technology requires new algorithms for effective use of VLSI chips. Thus, our research has considered several classes of problems and various algorithms for each class. We have also considered certain theoretical problems associated with the representation of processing systems. The reason alternate representations are important is that they suggest new and more general methods of uniting different processing tasks.

Some of the problems considered include:

(i) the processing of array data from arrays with a large number of sensors;

(ii) the processing of time-varying data for singular value decomposition and spectral estimation and tracking;

(iii) linear, time-invariant digital filtering;

(iv) the representation of processing systems using projection operators.

In the array processing problem, we have discovered a method of design for adaptive arrays that uses a fraction (such as 10%) of the total degrees of freedom in the array to adapt the array. The resulting arrays are called partially adaptive arrays. These results are summarized in several publications [11,17,20,22–24,26]. Also included in these publications are new implementations using newly designed systolic array-like structures.

The processing of time-varying data for digital processing tasks is an important problem in several applications. One portion of this problem common in many digital signal processing applications is the singular value decomposition of a data autocorrelation matrix. The eigenvalues of such a matrix are often a key component in the processing of data for tracking sinusoids in noise, for adaptive beamforming, and in similar applications. This research has resulted in some new updating algorithms for time-varying data that are efficient and highly parallel. These results are contained in publications [3,7,12,13,16,25,28–30].

The use of so-called orthogonal filters for linear digital filtering is a new design technique for VLSI technology. This class of filters has many desirable properties, including:

(i) excellent finite register effects

(ii) a modular and regular layout

(iii) automatic l_2 scaling

(iv) an ability to trade time-multiplexing for parallel computation

(v) a simple design procedure

The results of this research are contained in publications [1,4,5,8,27].

Finally, there are several publications which are generally concerned with the representation of dynamical systems used for digital signal processing. These include [9,15,19,21].